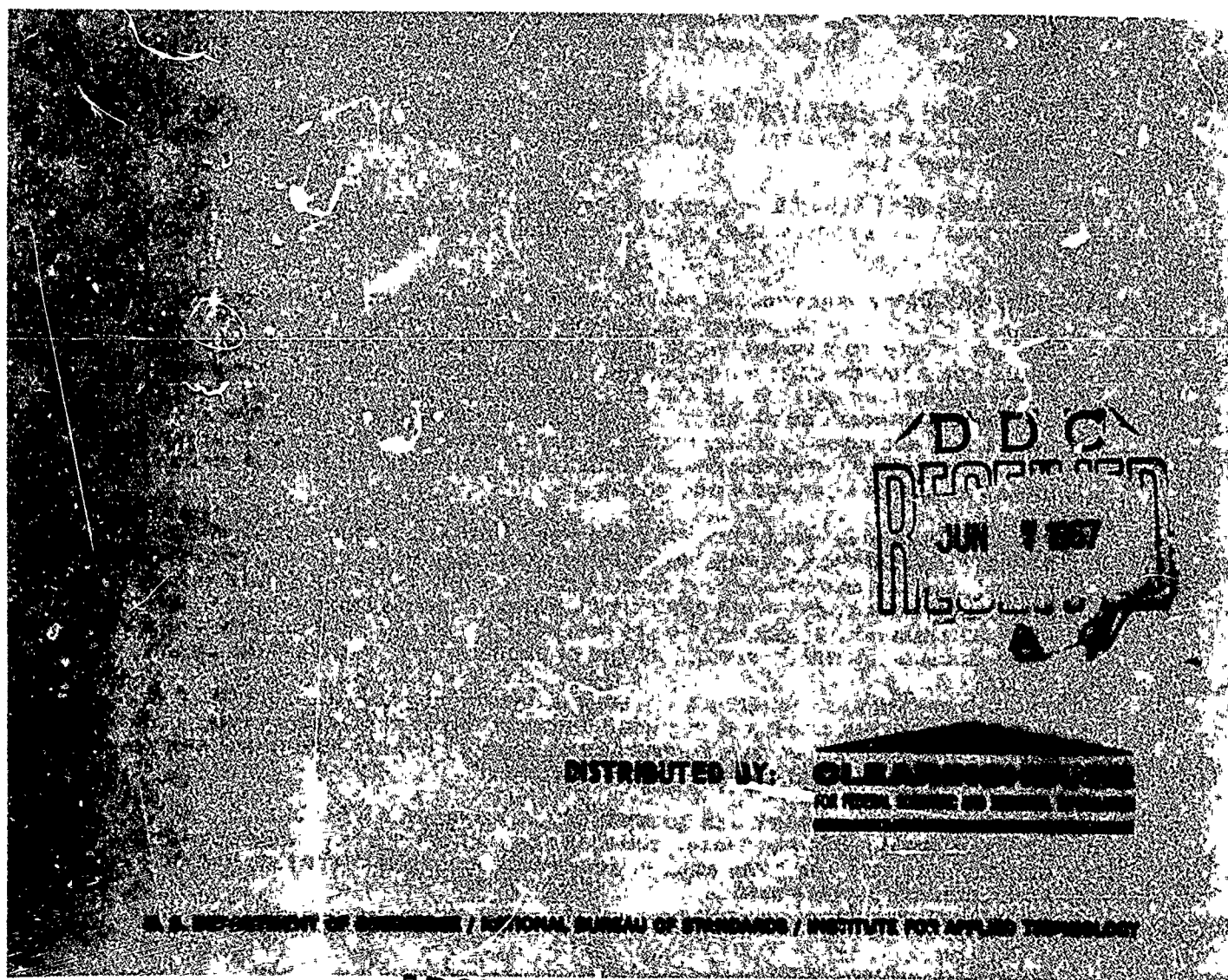


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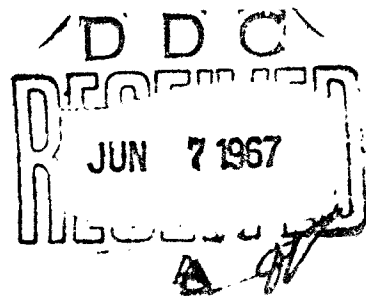
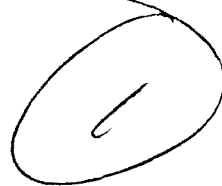
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THE DESIGN OF FLAT-SCORED HIGH-PRESSURE DIAPHRAGMS FOR
USE IN SHOCK TUNNELS AND GAS GUNS (U)

6 SEPTEMBER 1960



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U. S. NAVAL ORDNANCE LABORATORY
WHITE OAK, MARYLAND

UNCLASSIFIED
NAVORD Report 6865

Ballistics Research Report 29

THE DESIGN OF FLAT-SCORED HIGH-PRESSURE DIAPHRAGMS
FOR USE IN SHOCK TUNNELS AND GAS GUNS

Prepared by:

J. J. Rast

✓
ABSTRACT: An empirical design curve for flat-scored metal diaphragms is presented, which predicts burst pressures up to 40,000 psi. Also discussed are methods of holding the diaphragms and materials used in their fabrication. 11

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This report is a result of a study carried out to develop efficient and reliable high-pressure diaphragms for shock tunnels and gas guns and a method to predict their burst pressure.

This work was sponsored by the Re-Entry Body Section of the Special Projects Office, Bureau of Naval Weapons, under the Applied Research Program in Aeroballistics.

W. D. COLEMAN
Captain, USN
Commander

Z. I. SLAWSKY
By direction

NAVORD Report 6865

Table of Contents

	Page
List of Symbols	iv
Introduction	1
Design Curve	1
Material	2
Diaphragm Holders	3
Comparison of Flat and Hemispherical Diaphragms .	4
Conclusion	6

Illustrations

Table I	List of Diaphragms Used in Determination of Design Curve
Table II	P/E, t/a and ϵ_{au} For Scored Flat Diaphragms Listed in Table I
Figure 1	Typical Flat Diaphragm Holder Assembly
Figure 2	Typical Shock Tunnel
Figure 3	Typical Flat Diaphragm Holders
Figure 4	Burst Pressure vs. Thickness Ratio for Flat-Scored Diaphragms
Figure 5	Burst Pressure vs. Apparent Ultimate Strain for t/a Values of Experimental Flat Diaphragms
Figure 6	Experimental Diaphragms Used in Determination of Design Curve
Figure 7	Shear Failure of a Flat Diaphragm
Figure 8	Experimental Flat Diaphragms Used in the NOL 2-Stage 20-mm Gun
Figure 9	Flat Diaphragms With Integral Holder
Figure 10	Radial Deformation of Experimental Flat Diaphragms
Figure 11	Burst Pressure vs. Thickness Ratio for Flat & Hemispherical Diaphragms
Figure 12	A Time History of the 1.5-in. Gun Muzzle Trace-Comparison of Flat & Hemispherical Diaphragms of the Same Burst Pressure
Figure 13	Forged Hemispherical Muzzle Diaphragm & Rough Forging
Figure 14	Petal Failure Comparison of Forged vs. Machined Muzzle Diaphragms

LIST OF SYMBOLS

a,	in.	=	radius of unsupported area of the diaphragm
d,	in.	=	thickness of material left at the bottom of the groove
r,	in.	=	diaphragm bend radius
t,	in.	=	thickness of the diaphragm
E,	psi	=	modulus of elasticity
P,	psi	=	burst pressure
σ_{ult} ,	psi	=	ultimate strength (stress)
τ_{au} ,	psi	=	apparent ultimate strength
τ_{ult} ,	psi	=	shear ultimate strength
ϵ_{au} ,	in/in	=	apparent ultimate strain
ϵ_{ult} ,	in/in	=	ultimate strain

See Figure 1 for explanation of the above dimensions.

THE DESIGN OF FLAT-SCORED HIGH-PRESSURE DIAPHRAGMS
FOR USE IN SHOCK TUNNELS AND GAS GUNS

INTRODUCTION

1. Flat-scored metal diaphragms have been used successfully in the various hypersonic shock tunnels and gas guns at the Naval Ordnance Laboratory as quick-opening valves between the driver and driven gas chambers (Figures 1, 2 and 3). The diaphragms are essentially flat metal disks. They are grooved in order to adjust the burst pressure of the diaphragms and to minimize fragmentation. Upon reaching the predetermined burst pressure, the diaphragm ruptures along the base of the grooves forming petals which fold back against the sides of the holder. It is essential for efficient and safe operation to hold the burst pressure within close limits in order to allow the driver gas mixture to burn completely before the diaphragm bursts and still not be in danger of producing a hangfire. At the present time, in the NOL Shock Tunnels, these diaphragms are being used at burst pressures up to 40,000 psi with a typical pressure rise time of 15 milliseconds and a total flow duration of 10 to 15 milliseconds. Maximum total temperatures of the order of 2,500 to 3,000°K (4,000 to 5,000°F) are reached. These conditions are produced by igniting a hydrogen-oxygen-helium mixture in the driver gas chamber.

DIAPHRAGM DESIGN CURVE

2. Since it is desirable to be able to operate over a wide range of pressures, some systematic approach to the design of the diaphragm is necessary. This report presents a design curve (Figure 4) for flat-scored diaphragms based on existing diaphragm burst pressure data (Tables I and II and Figures 5 and 6). Table I is a list of diaphragms from which the data were obtained. Table II contains burst pressure data used in plotting the curves in Figure 5, which in turn was used to determine the final design curve, Figure 4. The use of this design curve facilitates the design of the diaphragm and provides a means for determining an optimum design for a given burst pressure. The set of curves is a plot of P/E versus t/a for a series of constant ϵ_{2u} values where $\epsilon_{2u} = (\sigma_{uh}/E)(d/t)$.

3. Flat diaphragms with burst pressures of 40,000 psi have been designed with the aid of these curves. They were made of type 305 annealed stainless steel plate. ϵ_{2u} was 0.0025

NAVORD Report 6865

assuming an ultimate stress of 85,000 psi. Best results are obtained with ϵ_{2u} values near 0.0023 for stainless steel. This gives a groove depth of 15 percent to 20 percent of the thickness. Shallower grooves will result in excessive shear stresses at the periphery of the diaphragm resulting in its failure. Figure 7 shows the results of a borderline case of two identical flat diaphragms burst under practically identical conditions. They were made of 305 annealed stainless steel. One of them retained all petals whereas the other one lost all petals through shear failure at the base. It was determined through measurements that the effective shear stress (τ) at failure was 104,000 psi which is in excess of the static ultimate tensile strength of the material. This is probably attributable to a shock loading effect, which should be further studied. By equating pressure force to resisting shear force one obtains:

$$P/E = 2(\tau/E)(t/a)$$

Assuming a working effective shear stress of 100,000 psi, a shear limit curve has been added to the design curve (see Figure 4). This limit is tentative upon further investigation. Low burst pressure diaphragms may require a lower ϵ_{2u} in order to keep the petals thick enough to prevent their burning off. For higher pressures, diaphragms with (t/a) values of .275 have been used. However, this appears to be approaching the practical upper limit for thickness. Thicker diaphragms do not fully open resulting in choking of the flow.

MATERIAL

4. The choice of material from which the diaphragm is to be fabricated is important. It must not only have reasonably high tensile and shear strength, but must be able to withstand a high degree of deformation without fragmenting. During the bursting process, the diaphragm must deform from a flat plate to a hemisphere and upon bursting fold back against the holder's cylindrical wall so as to prevent choking of the flow. If particles are shed (during this process) they attain extremely high kinetic energies in the flow and produce disastrous results upon striking expensive models and instrumentation in the test section.

5. Austenitic stainless steels appear to be the best choice of material. In the annealed condition, they have very high elongation and relatively high ultimate strength. They also

NAVORD Report 6865

have high values of specific heat, density, and melting point with a low thermal conductivity which aids in resisting petal erosion and failure. Types 304 and 305 appear to be the best choice of the austenitic stainless steels with 305 preferred because of its lower work hardening property.

6. An example of the extreme formability of annealed 304 stainless steel is illustrated in Figure 8. This flat diaphragm is 0.25-inch thick with an unsupported diameter of approximately 2.50 inches and has a design burst pressure of 15,000 psi. Although designed for a shock tunnel, it was used in the NOL 2-Stage 20-mm Gun between the chambers. It appears that the diaphragm opened to a nearly full position and then four of the six petals were bent backwards when a strong shock reflection produced a large pressure reversal across the diaphragm. There was no apparent loss of material and only minor cracks appeared at the base of the petals. Figure 8 also shows another flat 304 diaphragm of the same outside dimensions which was used in the same facility. It had shallower grooves which raised its design burst pressure to 30,000 psi. It was scored for six petals; however, it produced only three petals upon bursting. There was no serious cracking at the base of the petals.

7. It has been found through trial and error that a four-petal configuration produces the most consistent results with no serious cracking or fragmenting under normal conditions. However, if a detonation occurs in the driver chamber there is usually serious cracking of the petals and occasionally a loss of one or more of them.

8. Using 304 or 305 stainless steel, it has been found that the radius over which the petals are formed can be as low as $1/2 t$ although larger radii are preferable.

DIAPHRAGM HOLDERS

9. Flat diaphragms were originally used at NOL in a 20-mm shocktube wind tunnel and a .50-caliber gas gun by P. Aronson and T. Marshall, respectively. These diaphragms were used at relatively low pressures (4,000 - 6,000 psi) and had large flanges to resist radial forces tending to pull the diaphragm inward. As flat diaphragms began to be used in other facilities at higher pressures, various methods were used to prevent the pulling in of the flanges. The usual method was to have a lip on the outer edge that could be held positively by the holder.

NAVORD Report 6865

10. Another approach used by R. Stewart of NOL was to make the holder an integral part of the diaphragm, as shown in Figures 3a and 9. This utilized the same principle as used previously by B. M. Shepard in designing diaphragms for a 40-mm shocktube wind tunnel and has proved successful.

11. A series of plain flat diaphragms of the same configuration as used in the 20-mm Hypersonic Shock Tunnel and .50-caliber gas gun, have been designed and successfully burst at pressures of approximately 40,000 psi. The typical holder for this type is shown in Figure 3b. There is a noticeable "pull-in" as shown in Figure 10 but this is no more than noted on the integral holder types and has no detrimental effect on its performance. As the diaphragm deforms, the radial forces on the flange diminish, approaching zero as the diaphragm approaches a hemispherical shape. At the same time, the flange's resistance to "pull-in" increases as it is compressed tangentially. Therefore, the flange reaches an equilibrium point where it no longer "pulls in." The ratio of over-all diameter to the diameter of the unsupported area of these diaphragms is approximately 1.35 and appears to be adequate. A slightly smaller ratio could probably be used if necessary.

COMPARISON OF FLAT AND HEMISPHERICAL DIAPHRAGMS

12. Hemispherical diaphragms have been used in the belief that they could be designed for higher pressures and would have faster opening times than flat ones. The cost of fabricating these by the present means, however, is very high compared to the flat diaphragm. Present cost figures based on limited production indicate a cost ratio of about 5 to 1. The cost of the flat diaphragms could be further reduced if they were designed with standard stock thicknesses. This would eliminate the need for facing down the material to the proper thickness, which is, in most instances, the most time-consuming operation in the diaphragm's fabrication. The flat diaphragms mentioned are of the type having a uniform thickness and do not include ones with any type of flange variation for pull-in restraint purposes, the more elaborate of which have costs approaching that of the hemispherical type diaphragm. In view of the high cost differential, it seems worthwhile to investigate the advantages of the hemispherical configuration over the flat, if any, and under what conditions these advantages are worth the higher cost.

13. The approximate burst pressure of the hemispherical diaphragm is given by the equation:

$$P = 2\sigma_{ult} (d/a)$$

which is arrived at by equating the stress force at the bottom of the groove to the pressure force. For comparison with the flat diaphragm design curve (See Figure 11), this equation can be rewritten as:

$$P/E = 2(\sigma_{ult}/E)(d/t)(t/a) \quad \text{or} \quad P/E = 2\epsilon_{au}(t/a)$$

14. It appears from Figure 11, that for pressures below 15,000 psi and (t/a) values of less than 0.10 the hemispherical diaphragm is superior from the minimum thickness standpoint. However, as the thickness is increased for higher pressures, the effect of bending in the flat diaphragms becomes noticeable in resisting the pressure load resulting in higher burst pressures for the flat diaphragms. It is not fully understood, however, why diaphragms with high ϵ_{au} values which deform to a hemispherical shape before bursting, have higher burst pressures than hemispherical diaphragms of the same thickness and groove depth. It might be due to interaction of pressure rise time and the time necessary to deform the flat diaphragm or some work hardening phenomena produced by the deformation of the flat diaphragm.

15. Although there is no experimental verification, the author believes that there is little difference in the opening time of a properly designed flat diaphragm and a hemispherical diaphragm where the opening time is defined as the time from initial rupture to the time of full opening. It would appear though that there is a delay in the flat diaphragm from the time of application of pressure to the time of rupture because of the deformation process. This delay should have little or no detrimental effect where the diaphragm is used between the driver and the driven gas chambers.

16. However, this delay is important for muzzle diaphragms (between the driven chamber and nozzle). Here it is usually desirable to have the diaphragm open as rapidly as possible after reaching the desired burst pressure in order to minimize reflections of the shockwaves from the diaphragm. (The reflected shocktube wind tunnel is an exception to this.) Figure 12 is a comparison of muzzle pressure traces using a

NAVORD Report 6865

typical hemispherical diaphragm and a flat diaphragm which were used under identical conditions. Both diaphragms had static burst pressures of about 1,500 psi. The generation of a strong shockwave reflection by the flat diaphragm is obvious from the pressure trace. All petals were blown off of this diaphragm since the ultimate shear stress was reached at the periphery of the diaphragm before it had sufficient time to open.

17. Aside from the high costs, hemispherical diaphragms, fabricated by the usual means (turned from solid stock), have inherently poor grain orientation. This can be reduced by employing various heat treating processes. However, this is costly and not too reliable. A better method for both improving grain orientation and reducing cost is to hot-form the hemispherical diaphragms from flat blanks (Figure 13). Figure 14 compares a muzzle diaphragm machined from a solid blank with one finish machined from a hemispherical forging. Both are made from mild steel. The first one had consistent fractures at the base of the petals whereas the forged one had no such failures. The tips of the petals were lost due to the necessity of using a holder which was known to be too short for the diaphragm tested.

CONCLUSIONS

18. The design curve presented in this report has been useful in designing flat diaphragms. It could be further refined by conducting additional tests in which a set of diaphragms of varied thicknesses and groove depths would be burst under controlled conditions. The pressure rise time undoubtedly has an effect on the burst pressure and should be studied in more detail. It might be practical to derive a static burst curve similar to the curve presented here, to which an adjustment factor could be applied to account for various rise times.

19. Through experience it has been found that for best results at high pressures, up to 40,000 psi, the flat diaphragms should be made of 304 or 305 annealed stainless steel ($\sigma_{ult} = 85,000$) with $\epsilon_{au} = .0023$ referring to Figure 4. It should have four petals and a petal bend radius of $1/2 t$ or greater.

20. The flat diaphragm does not appear to be practical for use in the muzzle of standard shocktube wind tunnels because of the opening delay due to the deformation process. Here it is necessary to use hemispherical diaphragms or some other

NAVORD Report 6865

device. The flat diaphragm may be applicable and is being investigated for use as a muzzle diaphragm in reflected shocktube wind tunnels.

ACKNOWLEDGEMENTS




21. The author wishes to acknowledge the technical guidance provided by Mr. James L. Diggins under whose supervision this work was performed, and to thank Mr. Martin W. Wahler for his work in preparing the illustrations.

TABLE I
LIST OF DIAPHRAGMS USED IN DETERMINATION OF DESIGN CURVE

NO.	<u>SYMBOL</u>	<u>TYPE OF BURST</u>	<u>FACILITY USED</u>	<u>NOL</u> <u>DWG. NO.</u>	<u>DESIGNATION</u>	<u>NO. OF</u> <u>PETALS</u>	<u>DATA</u> <u>SOURCE</u>	<u>RE-</u> <u>MARKS</u>
1.	⊙	Dynamic	20-mm HST	-----	-----	4	P. Aronson	Avg. of 3 shots
2.	▽	Static	1.75 HST	Sk. 358130 pc. no. 2	4 - 3 F	6	P. Aronson	1- test
3.	△	Static	.50 cal. Gun	-----	-----	4	T. Marshall	Avg. 4 shots
4.	◇	Dynamic	1.5-in. HST No. 2	Sk. 506260 pc. no. 4	2.3 - 21	4	P. Aronson	Avg. 10 shots
5.	□ ₁	Static	4-in. HST No. 3	Sk. 358880	-----	4	H. Feather	1- test
6.	□ ₂	Static	4-in. HST No. 3	Sk. 358880	-----	4	H. Feather	1- test
7.	□ ₃	Static	4-in. HST No. 3	Sk. 358880	-----	4	H. Feather	1- test
8.	□ ₄	Static	4-in. HST No. 3	Sk. 358880	-----	4	H. Feather	1- test
9.	⊖	Dynamic	1.5 HST No. 1	Sk. 423772	1.9 - 37	6	J. Watt	Petals did not fully open
10.	▽ ₁	Static	1.5-in. Gun	Sk. 505947	-----	4	H. Carter	
11.	△ ₁	Dynamic	1.5-in. HST No. 1	Sk. 509485 pc. no. 3	2.0 - 37 F	4	J. Watt	1-shot
12.	△ ₂	Dynamic	1.5-in. HST No. 1	Sk. 509485 pc. no. 2	2.0 - 27 F	4	J. Watt	1-shot
13.	◇ ₁	Dynamic	1.5-in. HST No. 1	Sk. 506260 pc. no. 3	2.3 - 39	4	J. Watt	Avg. 7 shots

NAVORD Report 6865

TABLE I (cont.)

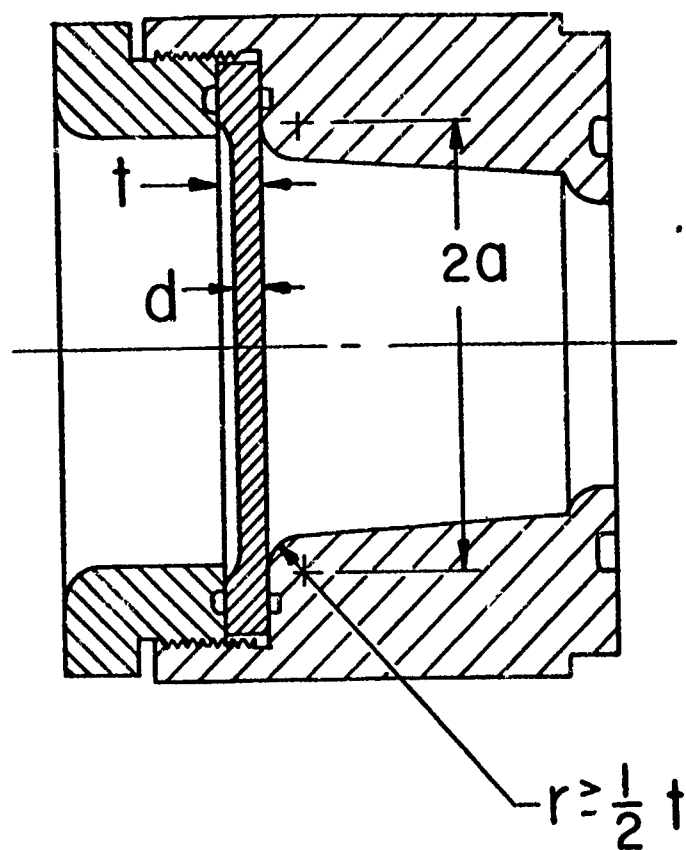
NO.	SYMBOL*	TYPE OF BURST	FACILITY USED	NOL DWG. NO.	DESIGNATION	NO. OF PETAIS	DATA SOURCE	RE- MARKS
14.		Dynamic	1.5-in. HST No. 1	Sk. 506260	2.3 - 31	4	J. Watt	1 shot
15.		Dynamic	1.5-in. HST No. 1	Sk. 506260 pc. no. 1	2.3 - 28	4	J. Watt	1 shot
16.		Dynamic	1.5-in. HST No. 1	Sk. 509488 pc. no. 3	2.5 - 43 F	4	J. Watt	1 shot

* Symbols used in Figure 5.

NAVORD Report 6865
TABLE II
P/E, t/a, and ϵ_{au} FOR SCORED FLAT DIAPHRAGMS LISTED IN TABLE I

NO.	MATERIAL	E psi 29×10^6	P psi	P/E 10^{-3}	t in.	a in.	t/a	σ_{ult} psi	d in.	d/t	ϵ_{au} 10^{-3}
1.	304 S.S.		4150	.143	.031	.64	.048	85,000	.021	.677	1.99
2.	321 S.S. (annealed)	"	1500	.052	.125	2.12	.059	85,000	.043	.344	1.01
3.	304 S.S. (annealed)	"	6100	.210	.059	.50	.118	85,000	.026	.441	1.29
4.	305 S.S. (annealed)	"	20,300	.700	.160	1.188	.135	85,000	.124	.775	2.27
5.	304 S.S. (annealed)	"	9700	.334	.250	2.64	.095	85,000	.156	.625	1.83
6.	1020 Steel as rolled	"	9300	.321	.250	2.64	.095	60,000	.219	.876	1.61
7.	1020 Steel as rolled	"	6800	.234	.250	2.64	.095	60,000	.188	.752	1.56
8.	304 S.S. (annealed)	"	5900	.204	.250	2.64	.095	85,000	.125	.500	1.47
9.	304 S.S. (annealed)	"	33,400	1.150	.284	1.031	.275	85,000	.150	.528	1.55
10.	304 S.S. (annealed)	"	21,000	.725	.188	1.150	.163	85,000	.113	.601	1.76
11.	305 S.S. (annealed)	"	37,500	1.292	.188	1.062	.177	85,000	.160	.851	2.50
12.	305 S.S. (annealed)	"	28,000	.966	.188	1.062	.177	85,000	.130	.691	2.02
13.	305 S.S. (annealed)	"	40,400	1.392	.225	1.188	.189	85,000	.192	.854	2.50
14.	305 S.S. (annealed)	"	32,300	1.112	.225	1.188	.189	85,000	.159	.706	2.07
15.	305 S.S. (annealed)	"	29,000	1.000	.225	1.188	.189	85,000	.145	.645	1.89
16.	305 S.S. (annealed)	"	38,500	1.330	.250	1.156	.218	85,000	.174	.696	2.04

NAVORD REPORT 6865



TYPICAL FLAT DIAPHRAGM
HOLDER ASSEMBLY

FIG. I

NAVORD REPORT 6865

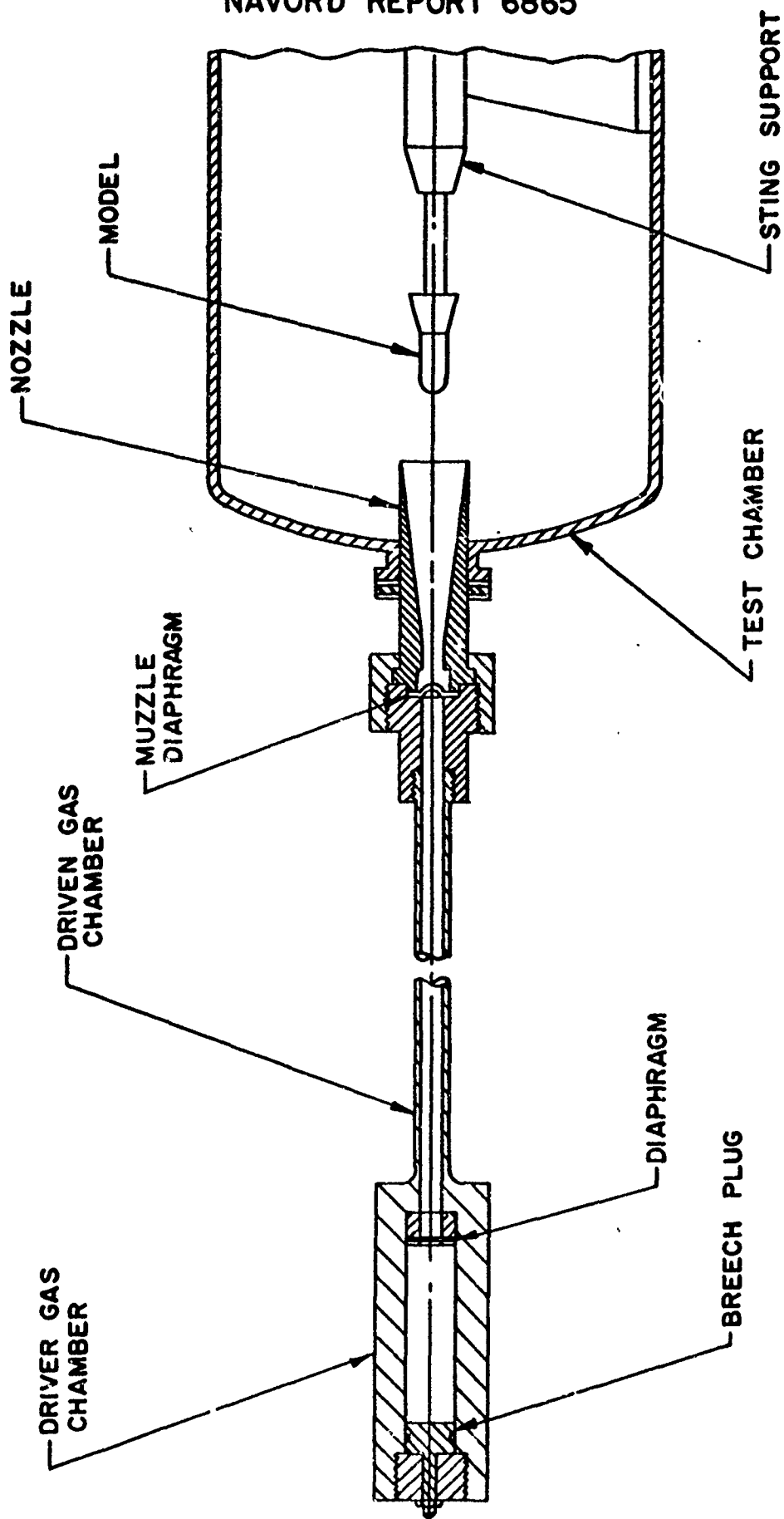


FIG. 2

TYPICAL SHOCK TUNNEL

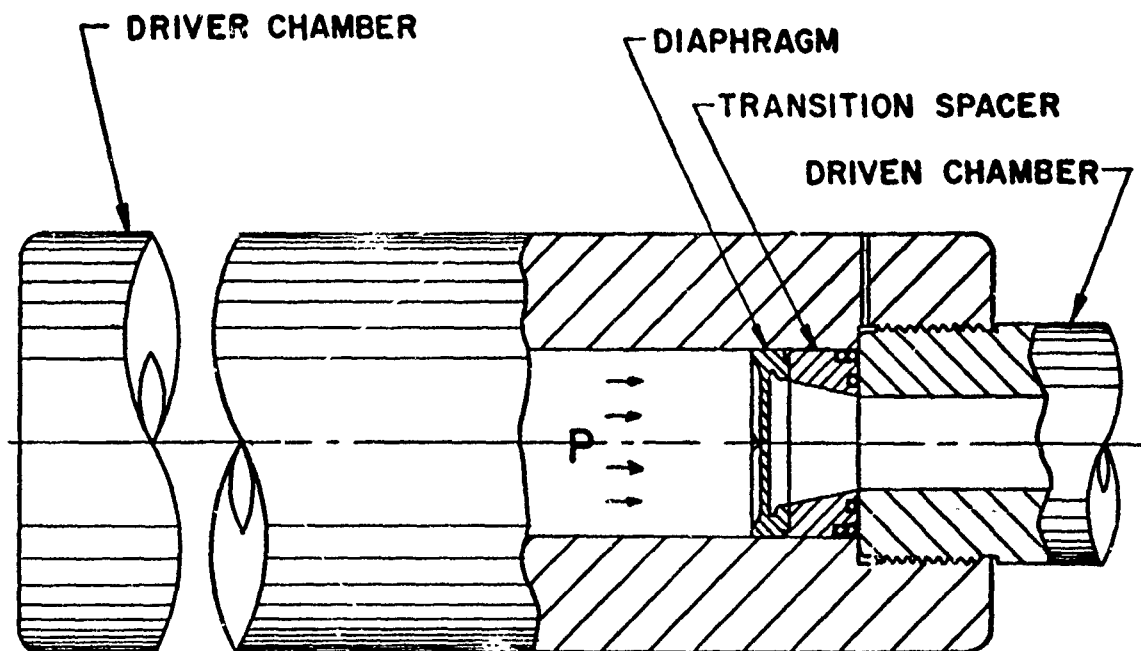


FIG. 3A

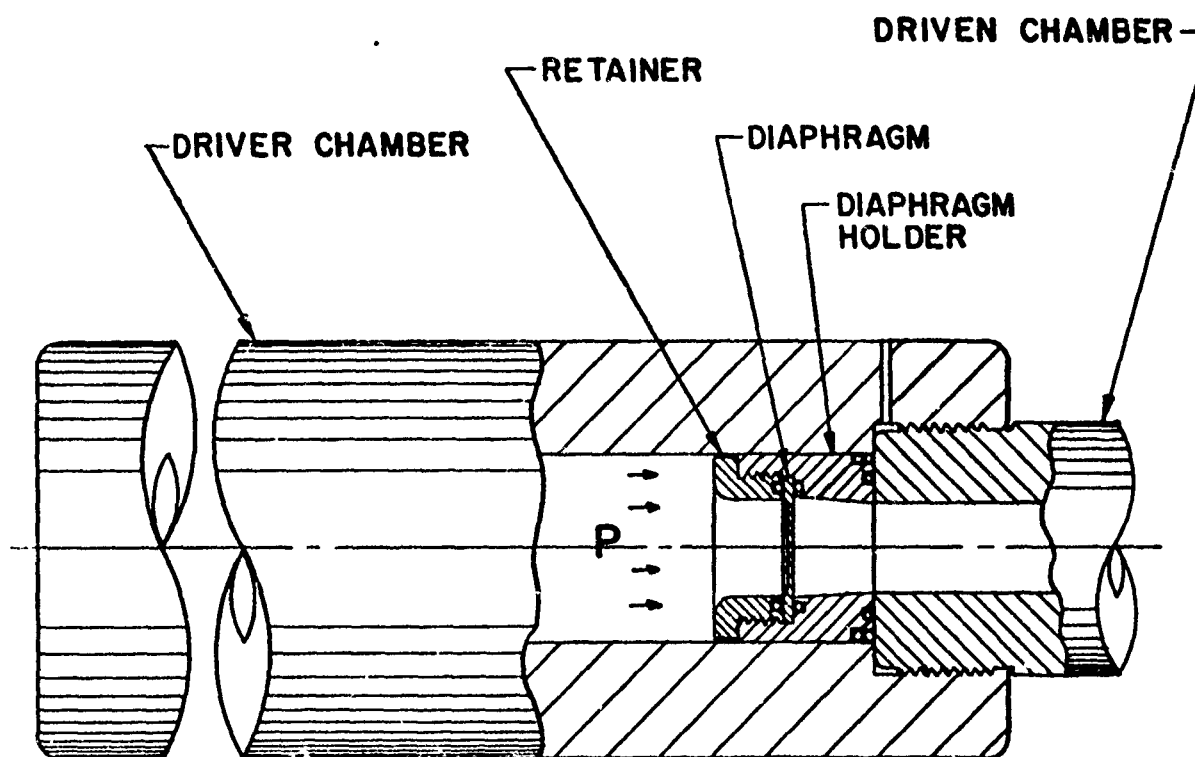


FIG. 3B

TYPICAL FLAT DIAPHRAGM HOLDERS

FIG. 3

BURST PRESSURE VS THICKNESS RATIO FOR FLAT SCORED DIAPHRAGMS

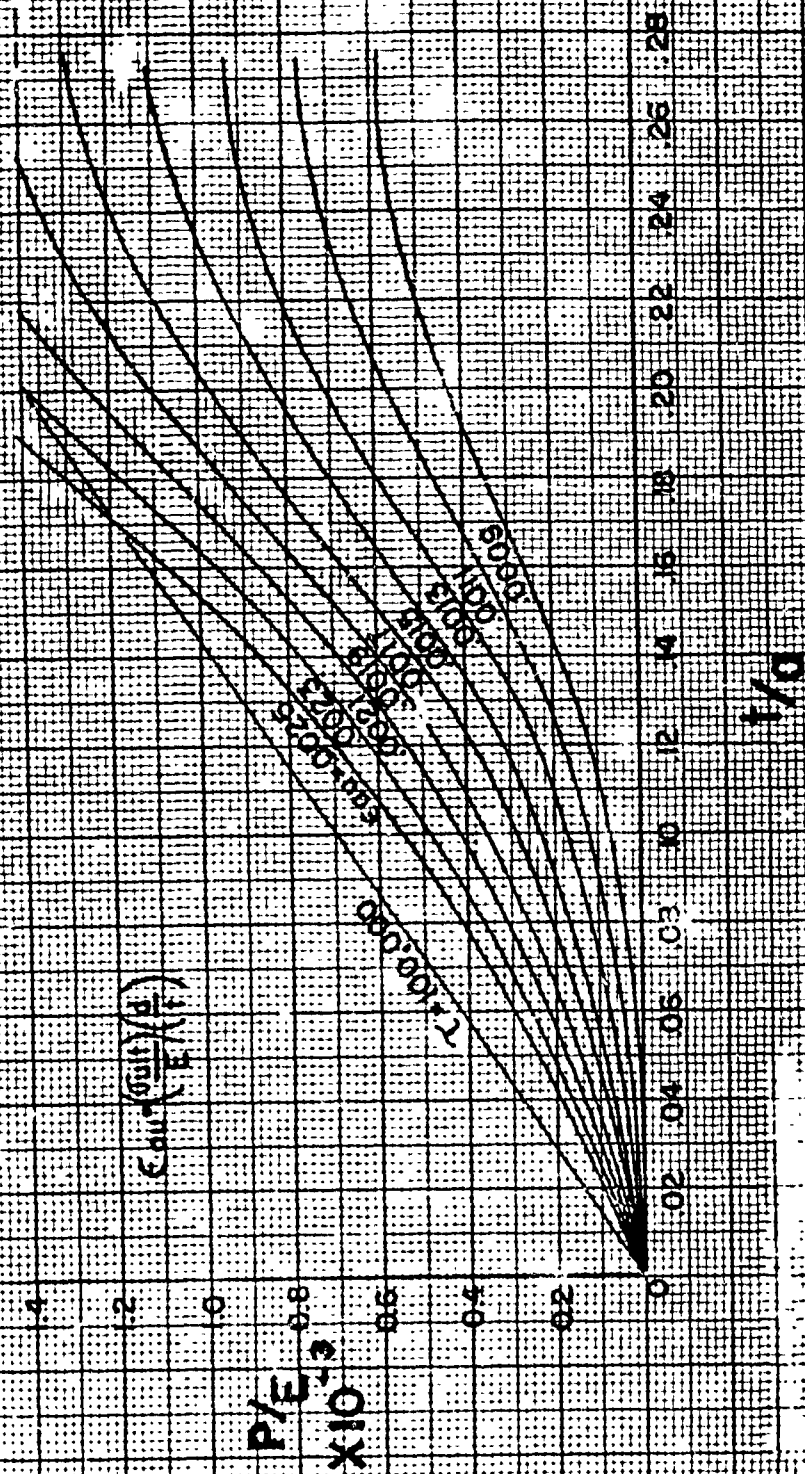


FIG. 4

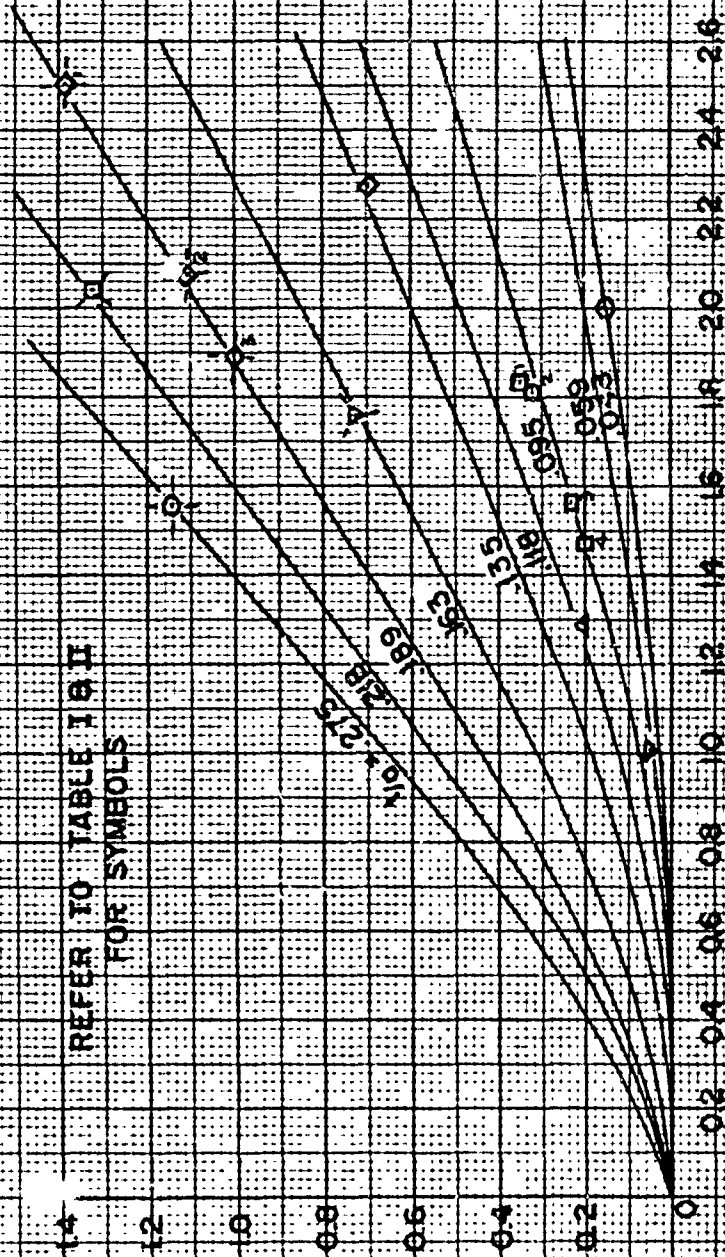
BURST PRESSURE VS APPARENT ULTIMATE STRAIN FOR $1/\alpha$ VALUES OF EXPERIMENTAL FLAT DIAPHRAGMS

REFER TO TABLE I & II
FOR SYMBOLS

FIG. 3

P/E^{-3}
 $\times 10^3$

$E_{00} \times 10^{-3}$ PSI.



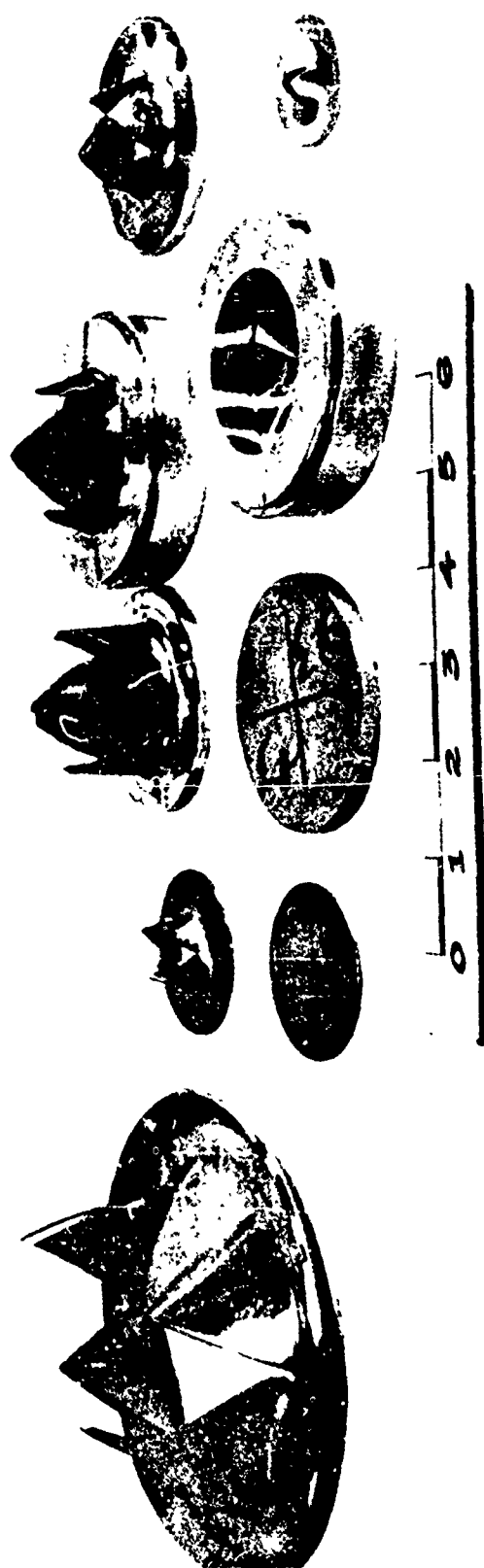


FIG. 6

EXPERIMENTAL DIAPHRAGMS USED IN DETER-
MINATION OF DESIGN CURVE.

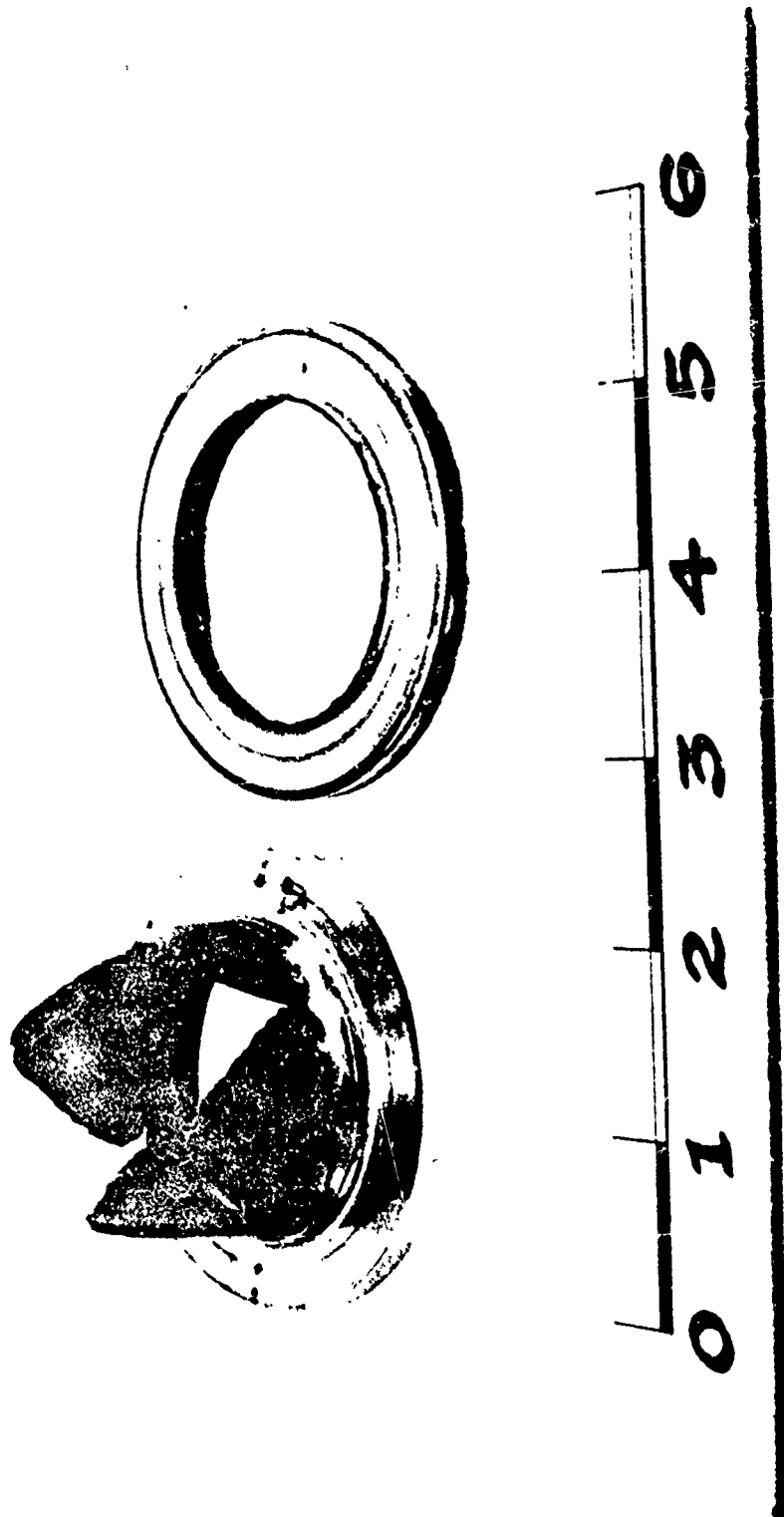


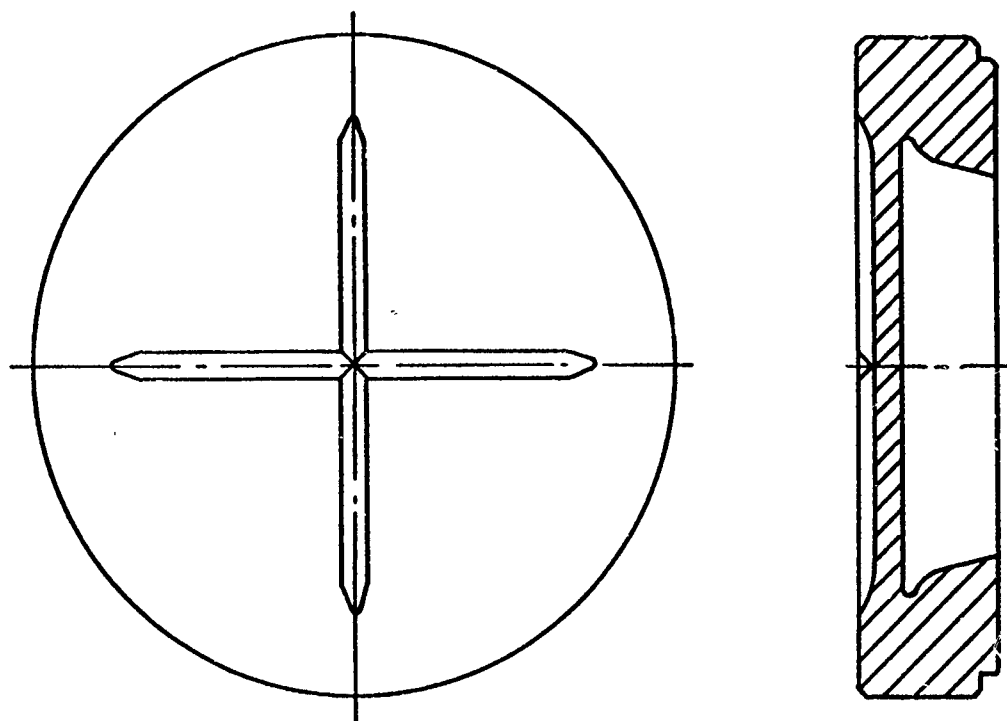
FIG. 7

SHEAR FAILURE OF A FLAT DIAPHRAGM



EXPERIMENTAL DIAPHRAGMS USED IN THE
2-STAGE 20MM GUN.

FIG. 8



**FLAT DIAPHRAGM WITH
INTEGRAL HOLDER**

FIG. 9

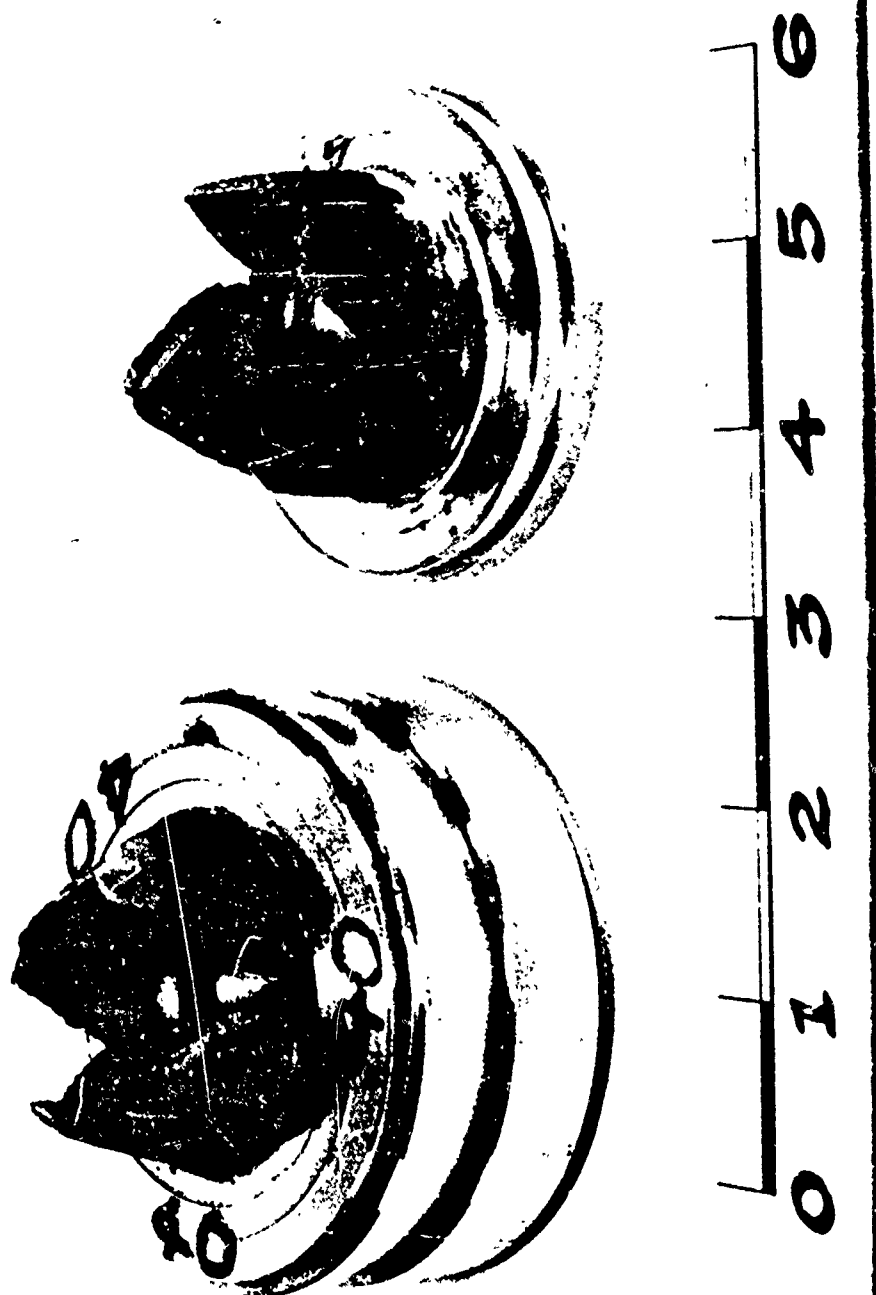


FIG. 10

RADIAL DEFORMATION OF EXPERIMENTAL
FLAT DIAPHRAGMS

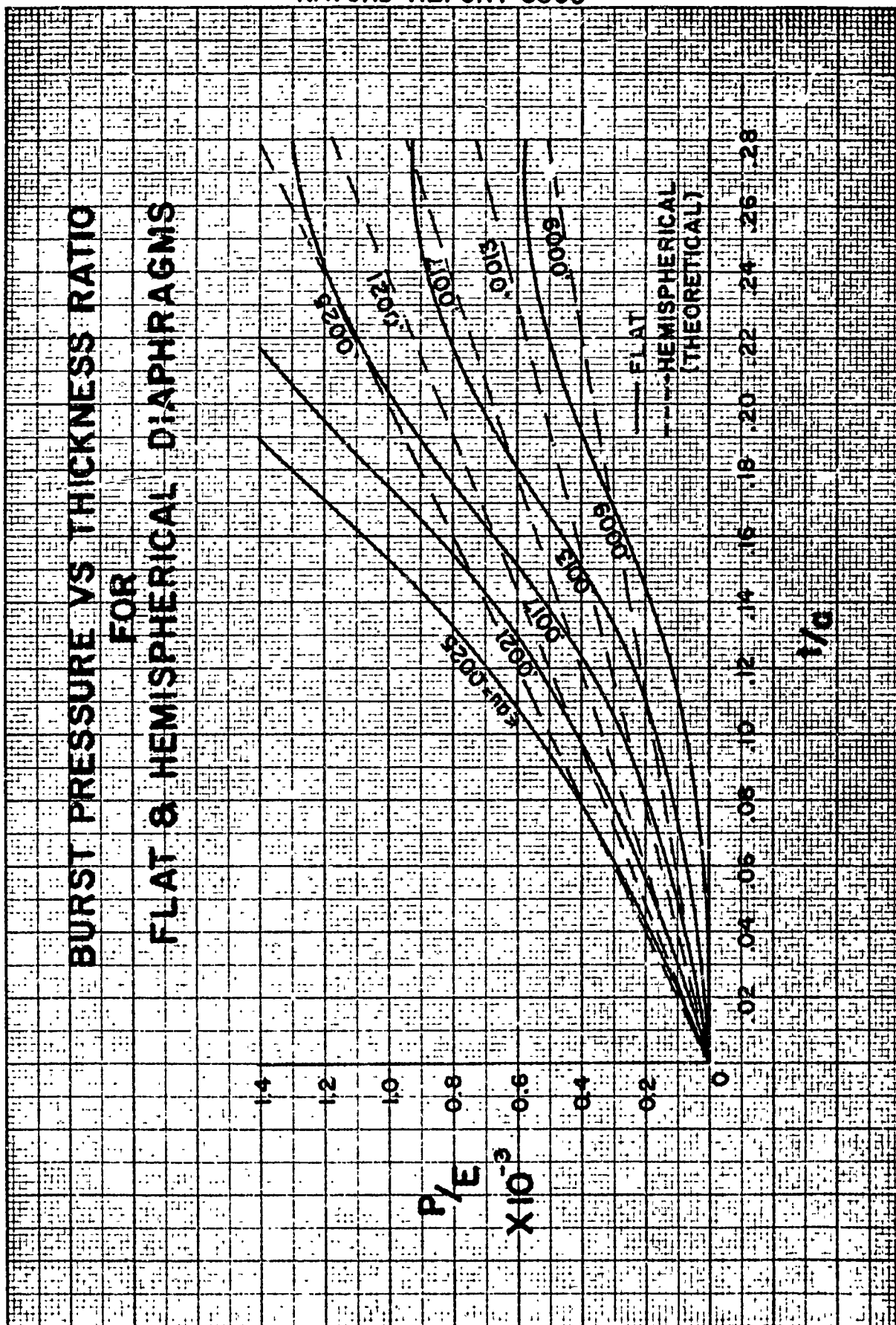


FIG. II

**A TIME HISTORY OF THE 1.5" GUN MUZZLE TRACE -
COMPARISON OF FLAT & HEMISPHERICAL
DIAPHRAGMS OF THE SAME BURST PRESSURE.**

NAVORD REPORT 6865

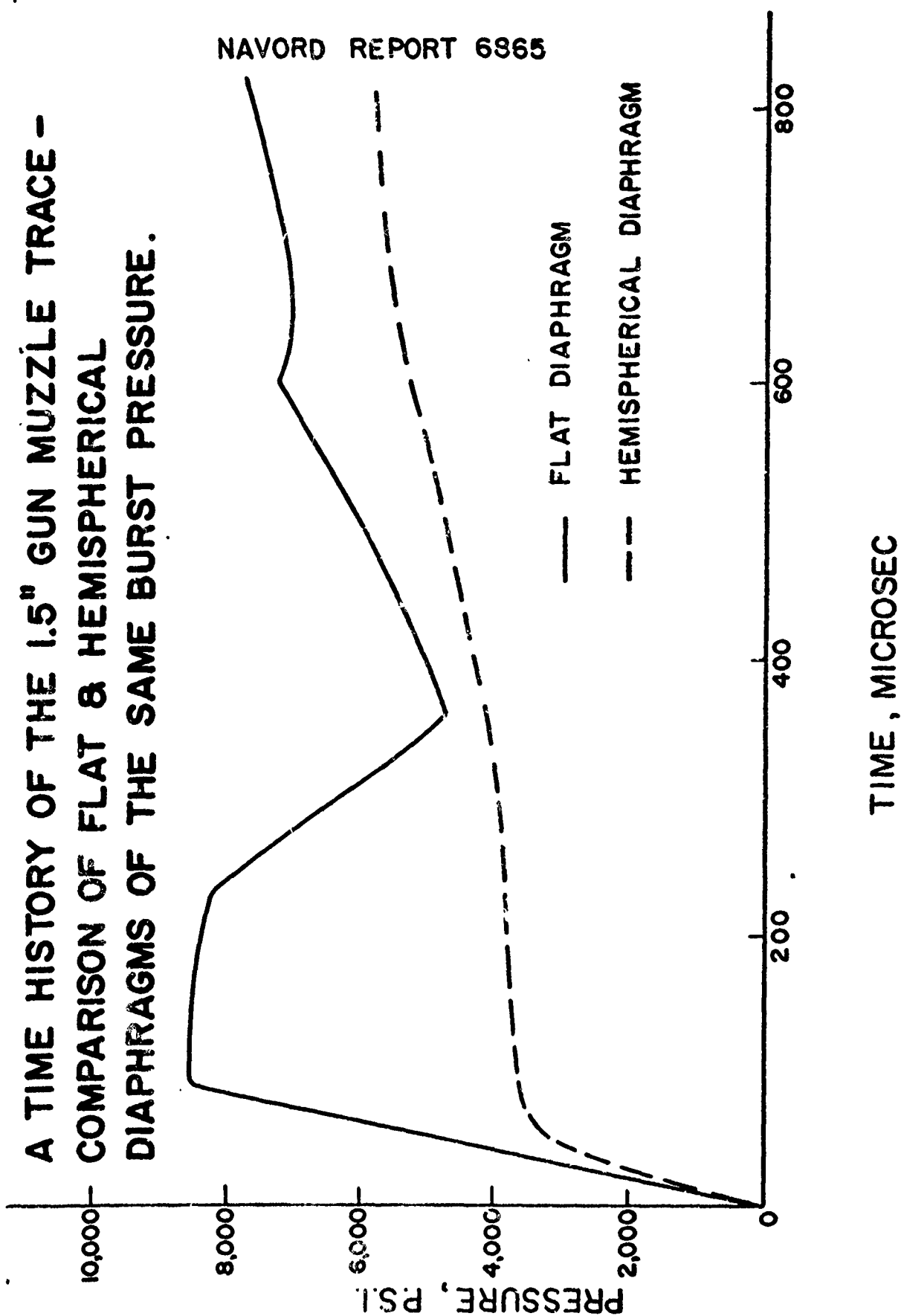


FIG. 12

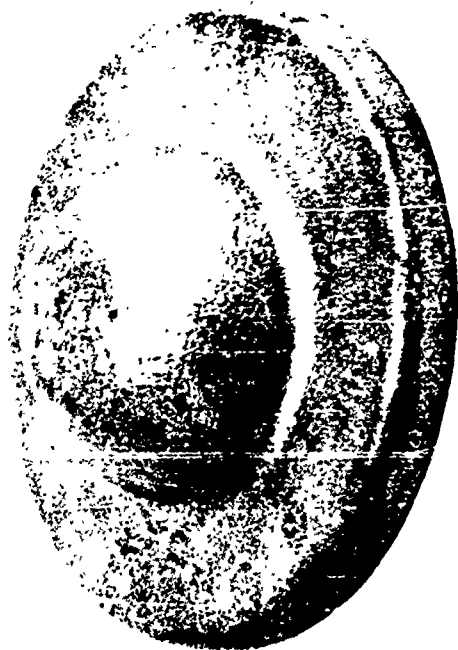


FIG. 13

FORGED HEMISPHERICAL MUZZLE DIAPHRAGM
AND ROUGH FORGING.



PETAL FAILURE COMPARISON OF FORGED VS
MACHINED MUZZLE DIAPHRAGMS

FIG. 14